

PPPL-4059

PPPL-4059

Edge Minority Heating Experiment in Alcator C-Mod

S.J. Zweben, J.L. Terry, P. Bonoli, R. Budny, C.S. Chang,
C. Fiore, G. Schilling, S. Wukitch, J. Hughes, Y. Lin,
R. Perkins, M. Porkolab, and the Alcator C-Mod Team

March 2005



PPPL Report Disclaimers

Full Legal Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Trademark Disclaimer

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

PPPL Report Availability

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Fiscal Year 2005. The home page for PPPL Reports and Publications is: http://www.pppl.gov/pub_report/

Office of Scientific and Technical Information (OSTI):

Available electronically at: <http://www.osti.gov/bridge>.

Available for a processing fee to U.S. Department of Energy and its contractors, in paper from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Fax: (865) 576-5728
E-mail: reports@adonis.osti.gov

National Technical Information Service (NTIS):

This report is available for sale to the general public from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: (800) 553-6847
Fax: (703) 605-6900
Email: orders@ntis.fedworld.gov
Online ordering: <http://www.ntis.gov/ordering.htm>

Edge Minority Heating Experiment in Alcator C-Mod

S.J. Zweben^a, J.L. Terry^b, P. Bonoli^b, R. Budny^a, C.S. Chang^c, C. Fiore^b,
G. Schilling^a, S. Wukitch^b, J. Hughes^b, Y. Lin^b, R. Perkins^a, M. Porkolab^b
and the Alcator C-Mod Team

^a Princeton Plasma Physics Laboratory, Princeton NJ 08540 USA

^b MIT, Cambridge Mass USA

^c New York University, New York

Abstract

An attempt was made to control global plasma confinement in the Alcator C-Mod tokamak by applying ICRH heating power to the plasma edge in order to deliberately create a minority ion tail loss. In theory, an edge fast ion loss could modify the edge electric field and so stabilize the edge turbulence, which might then reduce the H-mode power threshold or improve the H-mode barrier. However, the experimental result was that edge minority heating resulted in no improvement in the edge plasma parameters or global stored energy, at least at power levels of $P_{RF} \leq 5.5$ MW. A preliminary analysis of these results is presented and some ideas for improvement are discussed.

1. Introduction

In theory, the edge radial electric field (E_r) of tokamaks is determined at least in part by ion loss to the wall, and the E_r profile can in turn control the H-mode transition [1-5]. Edge electrode biasing experiments have certainly shown that an externally imposed radial current of ≈ 20 -200 A can create an H-mode-like transport barrier [6,7], and a clear correlation has been shown between edge potential changes and the L-H transition [8]. Thus it would be useful if some non-intrusive means could be found to control ion loss to the wall and thereby control the H-mode transition.

The present experiment was motivated by suggestions of Chang [9] and Perkins [10] that the edge E_r could be changed if a relatively small population of ICRH minority tail ions was created at the plasma edge and deliberately lost to the wall. For example, the radial ion loss current corresponding to 1 MW of tail ion loss at $T_{\text{tail}} \approx 10$ keV would be ≈ 100 A, i.e. comparable to the radial current in the edge biasing experiments. If the edge electric field could be controlled in this way, it might be possible to reduce the H-mode power threshold or improve the H-mode barrier in future magnetic fusion devices.

There have been many previous measurements showing a correlation between ion loss (or fast ions in the edge) and the edge electric field [11-14], but it has been difficult to establish a causal connection between the two in the absence of electrode biasing. An interesting attempt was made at DIII-D to deliberately create beam ion loss using counter-neutral beam injection [15]; however, this did not significantly affect the H-mode threshold or change the edge electric field [16]. The Electric Tokamak (ET) at UCLA was designed to create an electric field via ion minority tail ion loss [17], but definitive results have not yet been obtained.

This paper describes an attempt to use minority edge heating to control the edge electric field and H-mode transition in the Alcator C-Mod tokamak at MIT. Simplified estimates used in the design of this experiments are discussed in Sec. 2, the experimental results are in Sec. 3, preliminary modeling is in Sec. 4, and the conclusions are in Sec. 5.

2. Simple Estimates

This section describes simple estimates which were used to plan the present experiment. Some analysis of the experimental results is presented in Sec. 4.

Alcator C-Mod is a high field diverted tokamak with $B \leq 8$ Tesla, $I \leq 2$ MA, $R = 0.68$ m, $a = 0.22$ m, and a global energy confinement time of $\tau_E \approx 50$ msec. The ICRF frequency range used for this experiment was $f_{\text{ICRF}} \approx 78\text{-}80.5$ MHz, which is resonant with hydrogen minority ions at $B \approx 5.1\text{-}5.3$ Tesla, and the available ICRH power level was $P_{\text{RF}} \leq 5.5$ MW. Other details concerning C-Mod can be found elsewhere [18].

Since minority heating creates trapped ions, an approximate criterion for fast ion orbit loss is that distance from the banana orbit center to the wall “ δ ” should be less than the tail ion banana width Δ_{tail} , or roughly:

$$\delta < \Delta_{\text{tail}} \approx \varepsilon^{-1/2} q \rho_{\text{tor}} \quad [1]$$

where ε is the inverse aspect ratio, q is the edge rotational transform, and ρ_{tor} is the toroidal gyroradius of the fast ion. For the present experiment $\varepsilon^{-1/2} \approx 2$, $q \approx 5$, and typically $\rho_{\text{tor}} \approx 0.3$ cm, assuming for the moment a tail ion energy of $T_{\text{tail}} \approx 10$ keV at $B_{\text{tor}} = 5$ T. Therefore the minority resonance location needs to be within roughly $\delta \leq 3$ cm from the wall in order to deliberately lose tail ion banana orbits of this energy.

The ICRF power needed to form a minority ion tail is can be estimated from the Stix formula [19]:

$$P_{\text{RF}} \text{ (MW/cm}^3\text{)} \approx 3n_{\text{tail}} T_{\text{tail}} / \tau_s \quad [2]$$

where the fast ion slowing down time on the electrons is: $\tau_s \approx 6.3 \times 10^8 (A/Z^2) (1/\ln \Lambda) T_e (\text{eV})^{3/2} / n_e (\text{cm}^{-3})$, at least for $T_{\text{tail}} \geq 20 T_e$. For an assumed $n(\text{edge}) = 5 \times 10^{13} \text{ cm}^{-3}$,

$T_c(\text{edge})=100$ eV, $Z=M=1$, and $\ln \Lambda=20$, this implies $\tau_s \approx 1$ msec. Thus for a typical hydrogen minority fraction of $n_{\text{tail}}/n_e \approx 5\%$, an ion tail of temperature $T_i(\text{tail}) \approx 10$ keV should form at an ICRH power level of $P_{\text{RF}} \approx 10$ W/cm³. Assuming an ICRH heating volume corresponding to ≈ 3 cm wide region near the inner or outer plasma edge ($\approx 10^5$ cm³), this corresponds to an ICRH power level of $P_{\text{RF}} \approx 1$ MW.

Thus these simple estimates imply that an ICRH resonance applied in C-Mod within a few centimeters of the plasma edge at a power at a level of $P_{\text{RF}} \geq 1$ MW could create a minority ion tail with an energy $T_{\text{tail}} \geq 10$ keV, which would then be lost to the wall. The ion loss current corresponding to this process would be roughly $I_{\text{tail}} \approx P_{\text{RF}}/T_{\text{tail}} \approx 100$ amps, which is comparable to the current required for electrode-biased H-modes. In order to maximize the ion tail creation and loss, the edge density should be as low as possible to reduce the electron drag on the tail ion population, and the plasma current should be as low as possible to maximize the local q and banana width. Therefore these experiments were done at $I \leq 0.6$ MA and without additional gas puff fueling.

A simple estimate for the radial electric field due to ion loss can be adapted from the beam ion case analyzed by Parail [4]:

$$E_r \approx (n_{\text{tail}}/n_e)T_{\text{tail}}/\Delta_{\text{tail}} \quad [3]$$

Thus for the C-Mod parameters above this implies $E_r \approx 150$ V/cm. Alternatively, the E_r due to this ion loss can be estimated from the perpendicular conductivity [1-3], which is determined at least in part by the neoclassical ion-neutral collision frequency ν_{i0} :

$$\sigma_{\perp} \approx q^2(e^2 n_i / m_i) \nu_{i0} / \omega_{ci}^2 \quad [4]$$

The edge neutral density in C-Mod varies greatly vs. radius and poloidal angle [20], but using a typical value of $n_0=10^{10}$ cm⁻³ with $T_i \approx 100$ eV, $n_i \approx 5 \times 10^{13}$ cm⁻³, and $\rho_i \approx 3 \times 10^{-2}$ cm; then $\nu_{i0} \approx 10^3$ sec⁻¹, and $\sigma_{\perp} \approx 10^{-5}$ ($\Omega\text{-cm}$)⁻¹. Thus a tail ion loss of $I_{\text{tail}} \approx 100$ Amps

occurring over a radial scale length of ≈ 3 cm would change the radial electric field by $E_r \approx 100$ V/cm. Note that the neutral conductivity should dominate the effect of ion viscosity in these high density C-Mod discharges.

The electric field needed to affect the H-mode transition can be estimated in various ways based on existing theory [5]. The simplest way involves the properties of the edge turbulence, which are fairly well known in C-Mod [21]. To create an H-mode in the shear-stabilization model requires that the radial shear in the poloidal velocity V_{pol} is roughly: $dV_{\text{pol}}/dr \geq (L_{\text{pol}}/L_{\text{rad}})/\tau_{\text{auto}}$, where L_{pol} , L_{rad} , and τ_{auto} are the poloidal and radial correlation lengths and autocorrelation time of the edge turbulence. For C-Mod with $L_{\text{rad}} \approx L_{\text{pol}} \approx 1$ cm and $\tau_{\text{auto}} \approx 10$ μsec this implies the required poloidal flow shear for creating an H-mode would be created by an $E_r \approx 150$ V/cm over a radial distance of ≈ 3 cm (at $B=5$ Tesla), which is similar to the estimated effect of the 100 Amp ion loss.

Thus the expected electric field due to ion tail loss could be comparable to that required to affect the H-mode transition, at least within the context of these simple estimates. Of course, these are only order-of-magnitude estimates.

3. Experimental Results

Almost all the plasmas used in for these experiments had a plasma current of $I=0.6$ MA with the magnetic equilibrium shown in Fig. 1. The central electron temperatures and densities for these shots were typically $T_e(0) \approx 1$ keV and $n_e(0) \approx 1 \times 10^{14}$ cm^{-3} . The initial ICRH edge heating experiments were done at 78 MHz with $P_{\text{RF}} \leq 2.3$ MW, and in a second set the ICRH power was increased up to $P_{\text{RF}} \leq 5.5$ MW by the addition of ICRH power at 80.0 and 80.5 MHz (see Table 1). All the plasmas were done with a deuterium majority (except one shot with a helium majority), and all had a $\approx 5\%$ hydrogen minority concentration as measured by the H_α/D_α line ratio.

The ICRH hydrogen minority resonance location was varied from the inner edge

to the outer edge on a shot-to-shot basis by varying the toroidal magnetic field, as shown by the vertical lines for drawn $f=78$ MHz in Fig. 1 (see also Table 1). At the lowest field of $B=3.68$ Tesla the ICRH resonance was at $R_H = 47.4$ cm, i.e. 2 cm outboard of the inner separatrix at the midplane and 3.5 cm from the inner wall. At the highest field of $B=6.75$ Tesla field the ICRH resonance was at $R_H= 85.8$ cm, i.e. 3.5 cm outboard of the outer separatrix and 4.5 cm from the outer ICRH antenna-protection limiter at the midplane. For both cases the resonant surfaces extended into the scrape-off layer above and below the midplane due to the curvature of the flux surfaces, and in the high field case the resonance intersects the RF antenna. Ion orbit loss calculations based on these resonance locations are described in Sec. 4.1.

Figure 2 shows typical plasma parameters vs. time in this experiment, where in this case the hydrogen minority resonance was near the inner wall at $R_H=50.2$ cm and $P_{RF} \leq 4$ MW (#104022025). When the edge ICRH was applied there was no increase of the total plasma stored energy, at least above the initial Ohmic plasma level. There was also no increase in either the central electron temperature or DD neutron rate (not shown). However, there were often symptoms of (undesirable) ICRH coupling to the scrape-off layer plasma; for example, Fig. 2 shows the that with increased ICRH power there was an increase in the line averaged density, total radiated power, and average Z_{eff} . There was also an increase in the outer midplane D_α level (not shown), again indicating an increased recycling and/or impurity influx from the wall during edge ICRH heating.

Figures 3(a) and (b) show the dependence of the total stored plasma energy on the resonance location and ICRH power for the magnetic field scan of Fig. 1 (78 MHz only, #1030604020-32). For neither the inner nor the outer edge ICRH heating was there any significant increase in stored energy compared to the Ohmic plasma at these fields. In contrast, for the central heating cases at $B=5-6$ T the plasma stored energy increased by almost a factor of two with 1 MW of heating, corresponding to an H-mode transition (circled points). All typical signatures of H-mode were present in the central heating cases, e.g. n_e and T_e edge pedestal formation, initial D_α drop, etc. However, none of these characteristic signatures of H-mode were present in the edge heating cases, except

for an increase in line averaged density with RF, which was most likely due to an increased plasma-wall interaction.

Several variations on this scenario were tried in order to improve the null results of Figs. 3(a) and 3(b). As shown in Fig. 3(c), the ICRH power level was increased to $P_{\text{RF}} \leq 5.5$ MW with combined 78 MHz, 80 MHz, and 80.5 MHz for inner edge heating cases, but again there was no significant increase in the edge parameters or the global stored energy normally associated with an H-mode transition. Within this sequence of shots (#1040022021-30, see Table 1): (a) the ICRH antenna phasing was changed from the co-current to the counter-current direction (in contrast to the balanced cases in Fig. 3(a,b)), (b) the plasma current was reduced from 0.6 MA to 0.4 MA, and (c) a He majority plasma was tried instead of D majority (to vary the edge conditions). In all these cases the stored energy slowly decreased with increasing ICRH power, most likely due to some additional plasma-wall interaction during edge ICRH.

Figure 4 shows the dependence of the edge plasma density and temperature on the ICRH resonance location during the scan of Figs. 3(a,b) based on the edge Thomson scattering data averaged over a 2 cm wide region just inside the separatrix. For neither the inner nor the outer edge heating there was there any significant increase in edge parameters compared to the Ohmic plasma just before the ICRH was applied (although there were slight increases for the outer edge heating case). In contrast, with central heating at B=5-6 T the plasma edge parameters increased as expected for an H-mode in C-Mod (circled points).

Unfortunately, there were no direct measurements of fast ions, edge rotation, or edge electric fields available during this experiment. The standard C-Mod plasma cameras showed normal plasma-wall interactions, except for increased light where the resonance layer intersected the inner wall, and one small (non-damaging) arc where the resonant layer intersected the ICRH antenna.

Therefore the conclusion from these experiments was that edge ICRH minority heating did not create an H-mode and did not increase the stored energy in these Alcator C-Mod plasmas. Possible improvements are discussed in Sec. IV.

4. Preliminary Modeling

Theoretical modeling of this experiment is difficult and uncertain due to the unusual regime and the limited diagnostic information. Some preliminary results and limitations of such modeling are described in this section.

4.1 Fast ion loss boundaries

For the actual magnetic equilibrium and C-Mod limiter configuration, a Lorentz ($v \times B$ integrating) orbit code was used to calculate the fast ion loss boundaries in this experiment. An example of a hydrogen minority tail ion orbit for this experiment is shown at the left of Fig. 5, based on the EFIT equilibrium of Fig. 1. This ion was started with a pitch angle perpendicular to B at $R_H=49.7$ cm and $z=20$ cm, where a minority tail ion banana tip might lie for one of the inner-edge ICRH resonance locations ($B=3.82$ T). At energies less than 8 keV this orbit is confined, but 8 keV this orbit intersects the RF antenna limiter near the outer midplane.

The ion orbit loss boundaries for other resonance locations and initial z positions are shown at the right of Fig. 5. In general, these results are similar to the simple estimates of Sec. II, i.e. ions born near the edge can be lost at roughly ≈ 10 keV. Fig. 5 also shows that ions are more readily lost when started from the low- R_H edge resonance (as noted in Refs. 9 and 10), since banana widths for a given energy are larger for an orbit with its banana tip on the low- R_H edge compared with the high- R_H edge. For both inner and outer resonance location the ions are lost at the outer midplane, except for some cases in which they are lost through the X-point to the divertor region.

An unanticipated result of this modeling was that the ion energy required for an orbit to be lost for a given resonance location decreases significantly when the orbit banana tip lies above or below the midplane (i.e. for $|z| > 0$), as illustrated at the right of Fig. 5. This is because the banana orbits which are started at increased z lie on flux surfaces closer to the wall than for those started at $z=0$, and so their effective distance to the wall in terms of poloidal flux is decreased. Since ICRH minority heating occurs largely at the banana tips, at least for energetic ions, this implies that the ion tail loss depends on the vertical distribution of the ICRH heating power at a given resonance layer location.

4.2 ICRH modeling

Two of these edge heated discharges were modeled by the ICRH wave physics codes in TRANSP; namely, TORIC [22] and SPRUCE [23]. Inputs to this modeling were the magnetic equilibrium, the measured electron density and temperature profiles, the measured minority ion concentration ($\approx 5\%$), and the RF antenna structure and wave phasing. Outputs from this modeling were radial profiles of the ICRH power deposition, the hydrogen minority tail ion temperature, and the hydrogen minority tail ion loss power. Some limitations of this modeling are discussed in Sec. 4.3.

An example of the TORIC modeling is shown in Fig. 6 for a discharge with an inner edge resonance at $R_H=49.7$ cm (#1030604023). Fig. 6(a) shows that the ICRH power was largely deposited in the edge region according to this model (as expected). The total power absorbed in the edge was ≈ 1.3 MW out of a total of $P_{rf}=2.2$ MW applied at this time, corresponding to an RF power density of $\approx 1-3$ Watts/cm³ averaged over the edge flux surface, or $P_{RF} \approx 10$ Watts/cm³ locally. Of the absorbed RF edge power, 0.8 MW went to electron heating, 0.2 MW to ion heating, and 0.3 MW went into tail ion orbit loss. As shown in Fig. 6(b), the confined tail ion temperature for this case was up to $T_{tail} \approx 5$ keV about $r/a=0.8$. Assuming an average ion loss energy of 5 keV, the estimated ion loss current for this case was thus $I \approx 60$ A. An outer edge heating case with $P_{RF} \approx 1$

MW (#1030604030) modeled this way had a confined edge tail ion temperature of ≈ 2.5 keV and an estimated ion loss current of ≈ 150 A. The SPRUCE model predicted an ion loss current which was significantly lower than that inferred from the TORIC model, e.g. i.e. ≈ 15 Amps and 30 Amps ion loss for the inner and outer edge resonance cases, respectively. It is not understood why the predicted ion loss was larger for the outer edge heating case, since the orbit model of Sec. 4.1 showed that fast ions are more easily lost when their banana tips were at the inside edge.

Thus the ICRH modeling predicted that a hydrogen minority ion tail should form at the edge of these C-Mod plasmas, but the predicted tail ion temperature was not as high as the $T_{\text{tail}} \approx 10$ keV expected from the simple modeling. The predicted ion loss currents were in the range ≈ 15 -150 Amps, which is comparable to the currents used to create H-modes in the electrode biasing experiments [6,7]. However, there are many limitations, uncertainties and omissions in the modeling, as described in the next section.

4.3 Limitations of the modeling

In general, the fast ion orbit loss modeling of Sec. 4.1 should be quite accurate, but the ICRH modeling of Sec. 4.2 is preliminary and uncertain. Several potentially important effects not modeled at all, as described below; namely, “parasitic” absorption of ICRF waves, charge exchange of tail ions, and radial diffusion of minority tail ions. Given all these limitations, detailed modeling of the edge electric field was not attempted at this stage.

The ICRH power absorption mechanisms in the TRANSP ICRH models do not include any “parasitic” absorption processes such as sheath rectification, surface wave generation, and ionization in the edge and/or scrape-off layer. In the TRANSP model, if the ICRH power is not completely absorbed on the first pass through the plasma the power is reflected from the wall and continues to “multi-pass” until it is completely absorbed. However, a simple estimate based an analytic model of minority heating [24]

suggests that the single-pass hydrogen minority tail absorption fraction in the C-Mod edge may be only a few percent. Thus any comparable parasitic power loss in the SOL could significantly reduce the power input to the minority tail in this experiment. On the other hand, ICRH has been known to create fast ions in the edge through parametric processes even for central heating [25].

Charge exchange loss of the tail ions is also not included in the TRANSP/TORIC model. If the tail ions experience charge exchange within the closed flux surface region, they would be ‘lost’ without contributing to the radial current. For an assumed tail ion energy of 5 keV and an assumed neutral density of 10^{10} cm^{-3} , the charge exchange timescale is $\approx 10^{-3}$ sec. This is comparable to the fast ion thermalization time at the edge (see Sec. 2), so this effect might significantly reduce the lost ion current. It is difficult to be more quantitative without a better knowledge of the 2-D edge neutral density profile.

Finally, the minority tail ions might have a significant radial diffusion in the edge, since the edge is known to be highly turbulent (also the ICRH waves might cause radial diffusion). If the local ion diffusion coefficient is $D \sim 10^4 \text{ cm}^2/\text{sec}$, the time for the banana center to diffuse ≈ 4 cm to the wall would be $\approx 10^{-3}$ sec, also comparable to the fast ion thermalization time. This diffusion may be significantly reduced by ‘orbit averaging’ over the ≈ 1 cm scale edge turbulence. Again, it is difficult to be quantitative about this effect without a better understanding of the diffusion physics.

5. Conclusions and Possible Improvements

The goal of this experiment was to test whether edge ICRH minority heating in Alcator C-Mod could create a fast ion loss and increase the edge E_r , which in turn could improve the confinement. The experimental result was quite clear, as described in Sec. 3; namely, that edge heating caused no increase in the plasma confinement. The only effect of this edge heating was to slightly reduce the total stored energy, most likely due to recycling and/or impurity influx from the increased plasma-wall interaction.

Unfortunately, it is not possible at this stage to make a quantitative comparison of the (null) experimental results with the theoretical estimates of Sec. 4, since those estimates had such large uncertainties. It is not even possible to make a qualitative connection with the simple estimates of Sec. 2, since there was no direct measurement of the ion loss or radial electric field in this experiment. It is quite possible that the tail ion loss was less than expected, and so the resulting change in E_r was just not large enough to affect the plasma confinement.

One way to clarify the interpretation of this experiment would be to measure E_r just inside the separatrix either through edge rotation or a heavy ion beam probe. Fast ion loss could possibly be measured at the outer midplane using current collecting probes, and charge exchange measurements would be useful to confirm the presence of fast ions at the edge (but would not provide an absolute level ion loss).

The outcome of this experiment might be improved in C-Mod by reducing the edge density further to increase the tail ion energy, by increasing the edge ion temperature to improve the first-pass absorption of ICRH waves, or by reducing the SOL thickness to increase the fast ion orbit loss. A higher edge ion temperature should occur after an H-mode has been produced (e.g. with central ICRH heating); then if edge ICRH heating were applied, it might increase the H-mode pedestal further.

Large ICRH-induced edge fast ion loss might also occur in a device like JET, in which high edge ion temperatures have already been measured even without edge heating [14]. High edge ion temperatures have also recently been seen in NSTX during high-harmonic fast wave heating [25], although without any improved confinement.

References:

- 1) C.S. Chang et al, Phys. Plasmas 11, 2649 (2004)
- 2) T. P. Kiviniemi et al, Phys. Plasmas 10, 2604 (2003)
- 3) V. Rozhansky et al, Nucl. Fusion 42, 1110 (2003)
- 4) V.V. Parail et al, Nucl. Fusion **39**, 369 (1999)
- 5) J.W. Conner and H.R. Wilson, Plasma Phys. Control. Fusion **42**, R1 (2000)
- 6) R.J. Taylor et al, Phys. Rev. Lett. 63, 2365 (1989)
- 7) G. Van Oost et al, Plasma Phys. Cont. Fusion **45**, 621 (2003)
- 8) T. Ido et al, Phys. Rev. Lett. **88**, 055006-1 (2002)
- 9) C.S. Chang et al Phys. Fluids B3, 3429, 1991
- 10) F.W. Perkins, private communication (2001)
- 11) K. Ida, Plasma Phys. Control. Fusion **40**, 1429 (1998)
- 12) Y. Miura and JFT-2M Group, Nucl. Fusion 37, 175 (1997)
- 13) J. Noterdaeme and G. Van Oost, Plasma Phys. Control. Fusion **35**, 1481 (1993)
- 14) H. Weisen et al, Nucl. Fusion 21, 2247 (1991)
- 15) J. Kim et al, Plasma Phys. Control. Fusion **38**, 1479 (1996)
- 16) K.H. Burrell et al, Plasma Phys. Control. Fusion 46, A165 (2004)
- 17) R.J. Taylor et al, Nucl. Fusion **42**, 46 (2002)
- 18) I.H. Hutchinson et al, Phys. Plasmas **1**, 1511 (1994) ; E.S. Marmor et al, Nucl. Fusion **43**, 1610 (2003);
- 19) T.H. Stix, Nucl. Fusion **15**, 737 (1975)
- 20) R.L. Boivin et al, Phys. Plasmas **7**, 1919 (2000)
- 21) J.L. Terry et al, Phys. Plasmas **10**, 1739 (2003)
- 22) M. Brambilla, Nucl. Fusion **38**, 1805 (1998)
- 23) J. Ongena et al, www.carolusmagnus.net/papers/2003/docs/AT_12_Ongena.pdf
- 24) M. Porkolab, "Plasma Heating by fast magnetosonic waves in tokamaks", Advances in Plasma Physics, AIP Conference Proceedings, New York (1994)
- 25) J.C. Rost, M. Porkolab, R.L. Boivin, Phys. Plasmas **9**, 1262 (1992)
- 26) T. Biewer et al, to be published in Phys. Plasmas (2005)

Acknowledgements: We thank J. Hosea, D. Majeski, D. McCune, C.K. Phillips, R. Wilson, D. Rasmussen, and D. Darrow for help with this experiment. This work was supported by DOE contract DE-AC02-76CHO3073 (PPPL) and USDOE Cooperative Agreement DE-FC02-99ER54512 (MIT).

Table 1: Shot list

Shot #	B (T)	I (MA)	P _{RF} (MW)	R _H (cm)
1030604020	5.44	0.6	0	71.1
1030604021	5.40	0.6	1.1	54.8
1030604022	4.20	0.6	1.6	49.7
1030604023	3.83	0.6	2.3	49.7
1030604024	3.82	0.6	0.9	49.7
1030604025	3.68	0.6	0.9	47.8
1030604026	3.68	0.6	0.9	47.8
1030604027	3.68	0.6	0.7	47.8
1030604028	3.68	0.6	2.3	47.8
1030604029	5.95	0.6	0.9	77.4
1030604030	6.65	0.6	0.9	85.8
1030604031	5.44	0.6	0.9	71.1
1030604032	6.74	0.6	1.6	71.1
1040220021	3.86	0.6	5.5	49.3
1040220022	3.86	0.6	5.0	49.3
1040220023*	3.86	0.6	4.2	49.3
1040220024^	3.86	0.6	4.9	49.3
1040220025	3.79	0.6	4.2	50.2
1040220026	3.86	0.4	4.2	49.3
1040220027	3.86	0.4	4.9	49.3
1040220028	3.79	0.4	4.2	50.2
1040220029	3.86	0.6	5.0	49.3
1040220030#	3.86	0.6	5.0	49.3

* co-current RF phasing

^ counter-current RF phasing

Helium majority

Figure Captions:

Fig. 1: Typical plasma equilibrium and ICRH hydrogen minority resonance locations for this experiment. The resonance location R_H was scanned from the inner edge to the outer edge (on a shot-to-shot basis) by varying the toroidal field from $B=3.68$ Tesla ($R_H=47.8$ cm) to $B=6.74$ Tesla ($R_H=87.6$ cm), while keeping the plasma current fixed at $I=0.6$ MA. Intermediate ICRH resonance locations are indicated by the gray lines.

Fig. 2: Time dependence of plasma parameters during a typical shot in this experiment (#104022025). The RF power was modulated at 10 Hz to help isolate possible changes due to edge heating effects. The plasma stored energy does not increase with edge ICRH, at least with respect to its initial Ohmic values. However, there were some indications of an increased plasma-wall interaction with edge ICRH, e.g. increases in line average density, Z_{eff} , edge D_α and radiated power.

Fig. 3: Parts (a) and (b) show the total plasma stored energy vs. ICRH power and resonance location for the B field scan of Fig. 1 at $P_{\text{RF}} \leq 2.3$ MW and 78 MHz. There was no significant increase in stored energy with either inner or outer edge heating; however, with central ICRH heating (circled points at $B=5-6$ T) H-modes were created and the stored energy increased. Part (c) shows the stored energy vs. ICRH power for $P_{\text{RF}} \leq 5.5$ MW with combined 78, 80, and 80.5 MHz inner edge heating. Again, there was no significant increase in stored energy with edge heating. Each point on these plots corresponds to a single 0.1 sec heating pulse such as shown in Fig. 2.

Fig. 4: Edge electron temperature (top) and edge electron density (bottom) with and without edge minority heating. These measurements were made by Thomson scattering, and integrated over a region which maps magnetically from 0 to 2 cm inside the outer midplane separatrix (87-89 cm). The edge resonance location is shown at the bottom. Neither the inner nor outer edge resonance heating produced any significant increase in edge density or electron temperature. However, the central heating cases (circled points at 5-6 Tesla) did produce increased edge parameters characteristic of an H-mode.

Fig. 5: At the left is a typical hydrogen minority ion loss orbit for an inner edge resonance with a banana tip location of $R=49.7$ cm and $z= 20$ cm, Ions with this banana tip location will be lost to the wall at an energy ≥ 8 keV. At the right is the loss boundary for ions with banana tips at a specified R_H and z (height above midplane). Ions with an inner edge resonance are more easily lost than ions at the outer edge resonance, and for a given R_H the energy needed for loss decreases significantly with $|z|$ (all points with $|z| \leq 20$ cm lie inside the closed flux surface region).

Fig. 6: Calculation of the ICRH minority tail properties by the TRANSP/TORIC code for one of the inner wall resonance cases ($B=3.83$ T, $R_H=49.7$ cm, shot #1030604023 at 1.22 sec). Part (a) shows the ICRH power balance, and part (b) shows the confined minority tail ion temperature profile vs. radius. In this case ≈ 1.3 MW of ICRH power was deposited near $r/a=0.8$, resulting in a confined ion tail temperature of ≈ 5 keV. The calculated minority ion tail loss was ≈ 0.3 MW, which corresponds to ≈ 150 Amps of ion loss current.

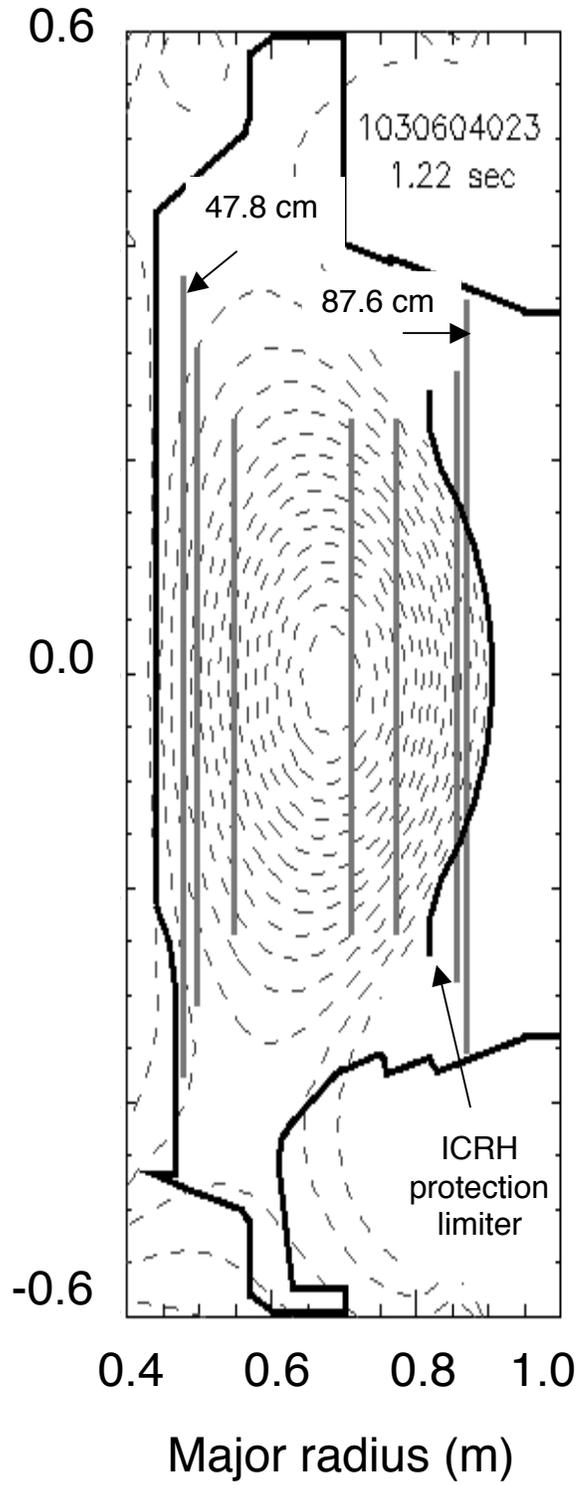


Fig. 1

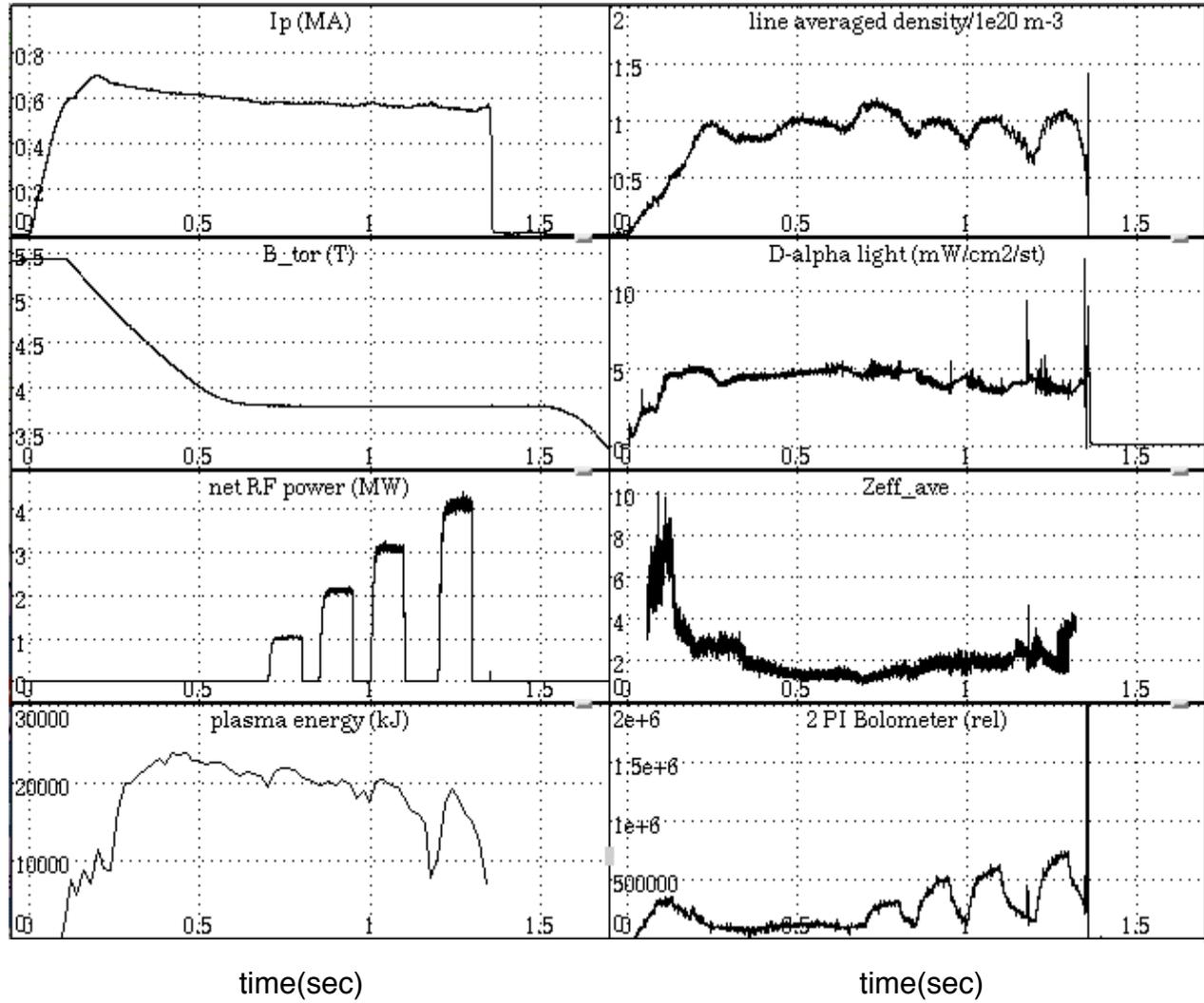


Fig. 2

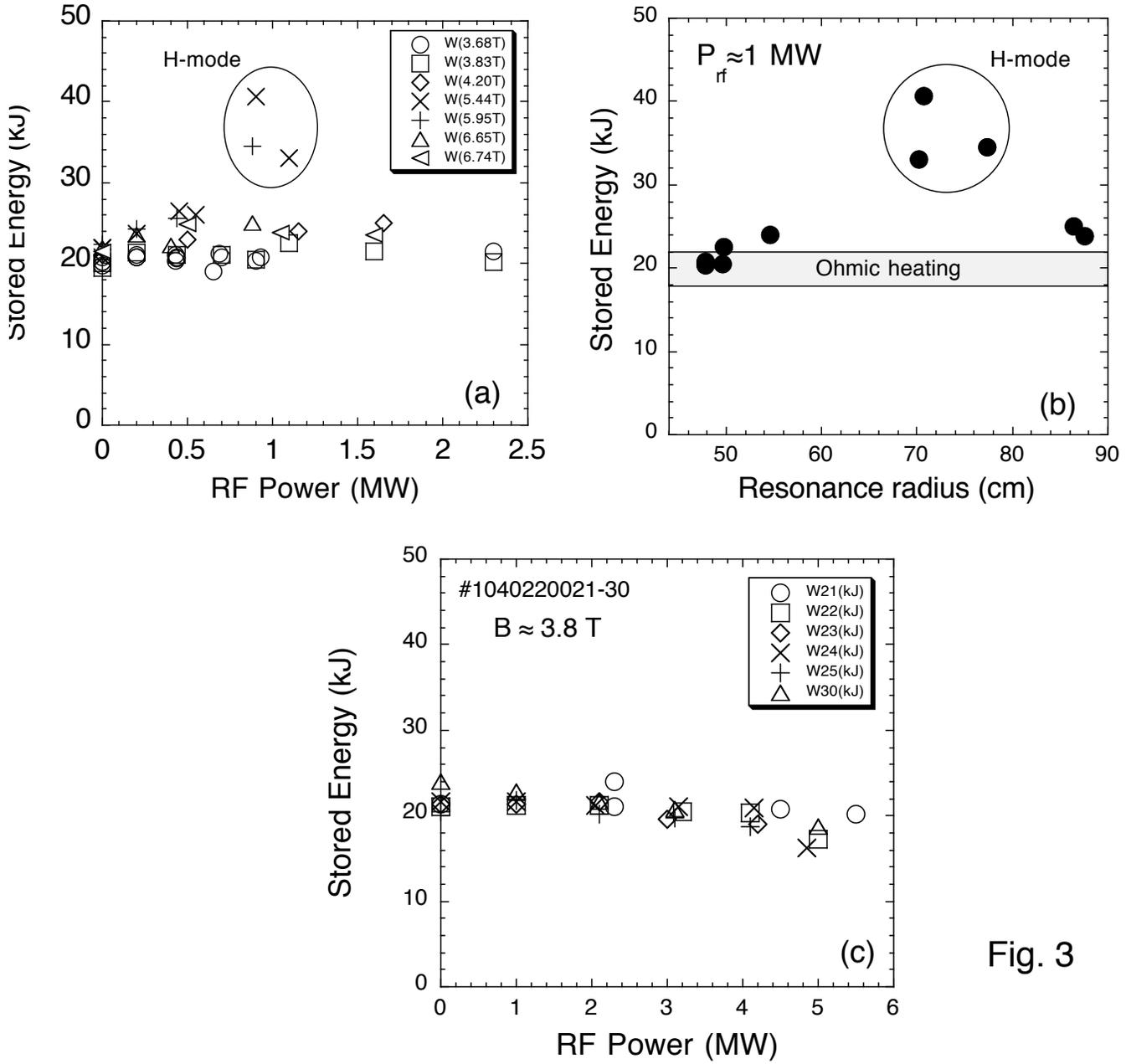


Fig. 3

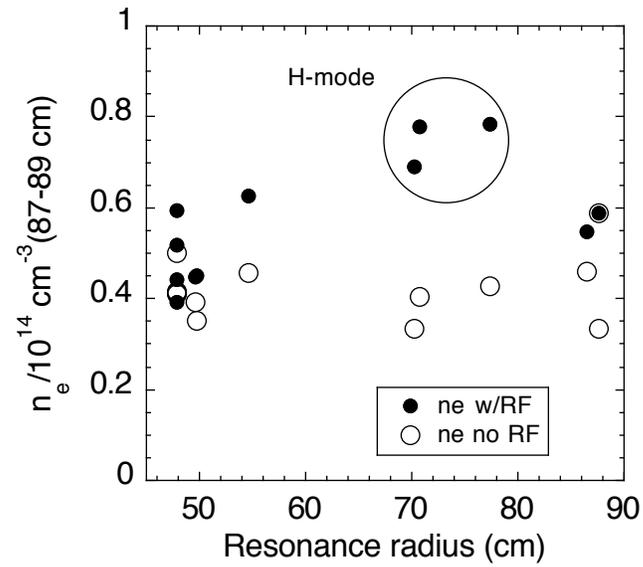
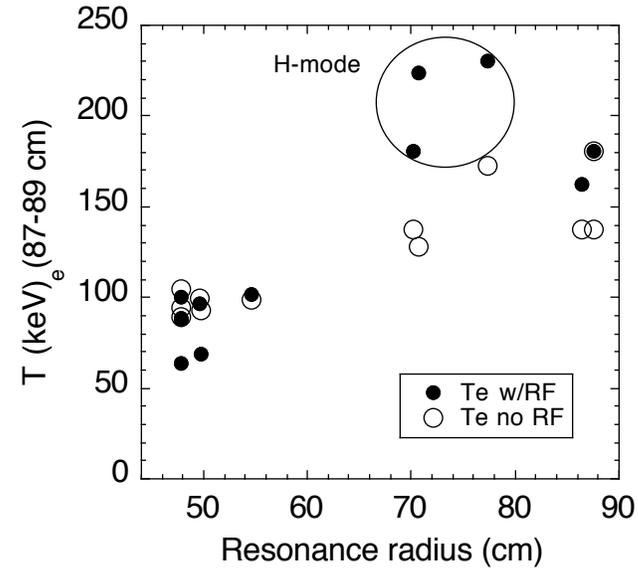


Fig. 4

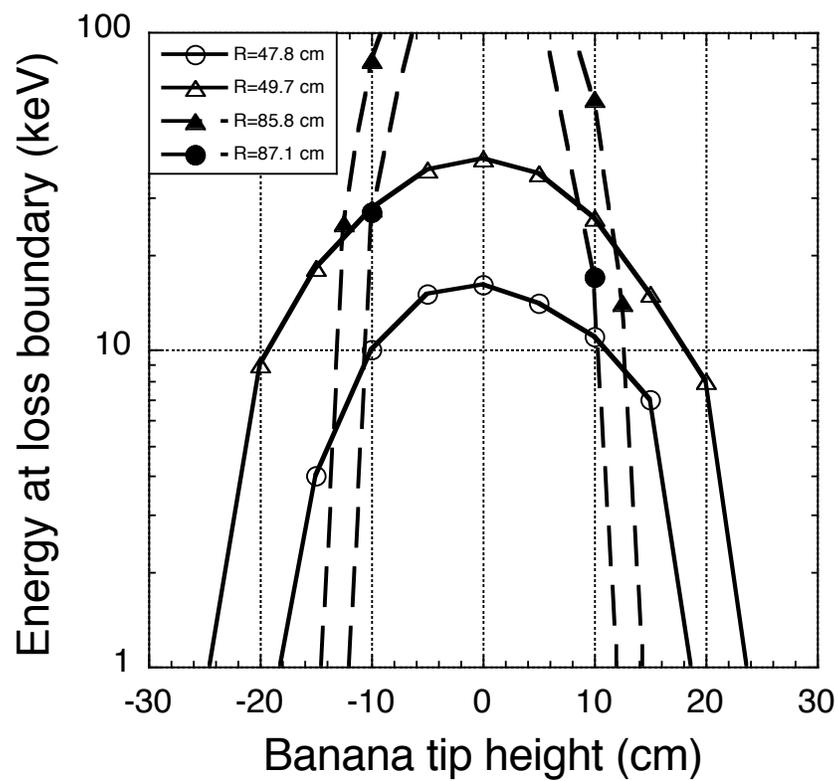
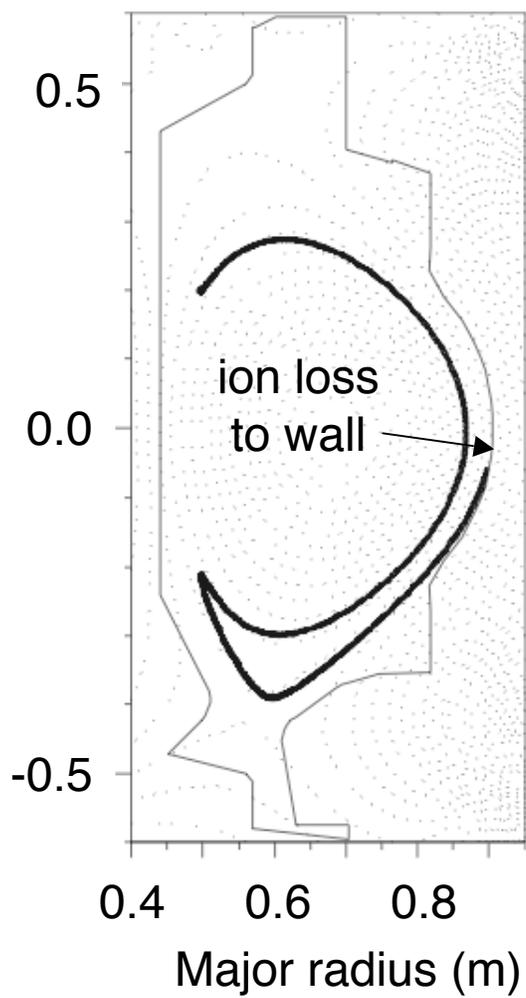


Fig. 5

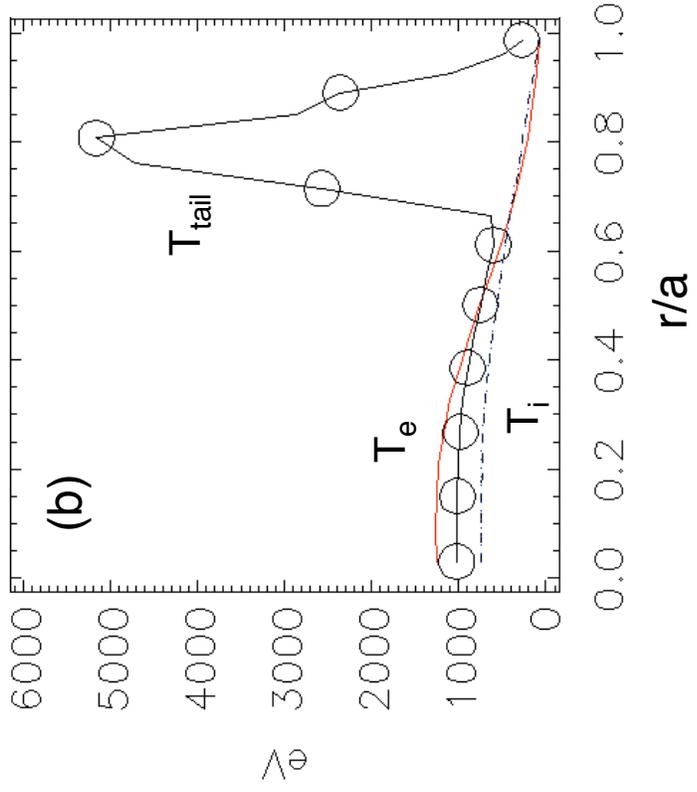
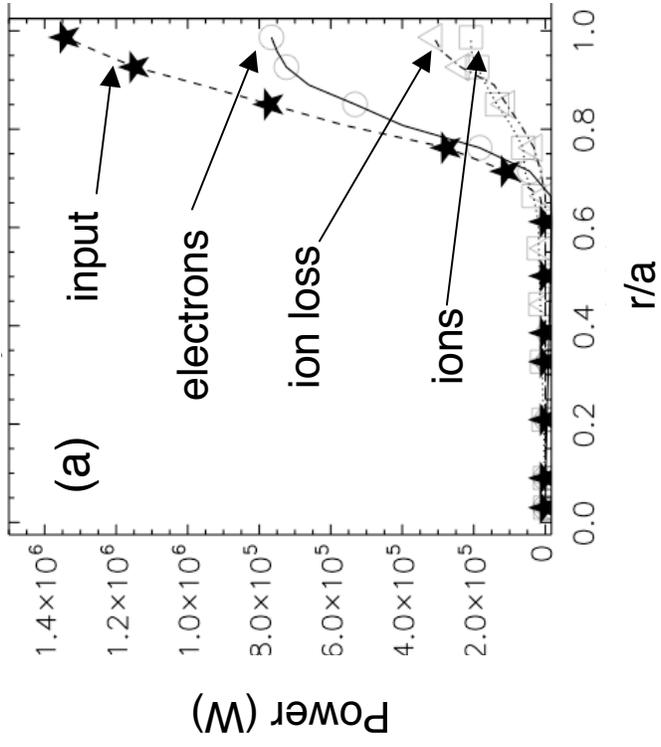


Fig. 6

External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Science Center, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, Hungarian Academy of Sciences, Central Research Institute
for Physics, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Institute for Plasma Research, India
Dr. Pandji Triadyaksa, Fakultas MIPA Universitas Diponegoro, Indonesia
Professor Sami Cuperman, Plasma Physics Group, Tel Aviv University, Israel
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Istituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Laboratory for Complex Energy Processes, Institute for Advanced Study,
Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Dr. Jiangang Li, Institute of Plasma Physics, Chinese Academy of Sciences,
People's Republic of China
Professor Yuping Huo, School of Physical Science and Technology, People's Republic of China
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Librarian, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2,
Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Dr. Rasulkhozha S. Sharafiddinov, Theoretical Physics Division, Institute of Nuclear Physics,
Uzbekistan
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California
at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Dr. John Willis, U.S. Department of Energy, Office of Fusion Energy Sciences, USA
Mr. Paul H. Wright, Indianapolis, Indiana, USA

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: <http://www.pppl.gov>